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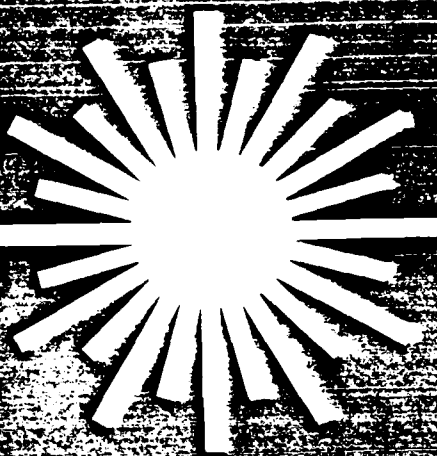
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ANNUAL TECHNICAL REPORT

"Air Force Ultrafast Optical Electronics
Center"

1987

Laboratory for Laser Energetics

University of Rochester
College of Engineering and Applied Science

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ANNUAL TECHNICAL REPORT
"Air Force Ultrafast Optical Electronics
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1987

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<p>The general objective of the AFOSR URI Center at Rochester is to investigate the physics of electronic microstructures using ultrafast optical techniques. To achieve this goal, we have developed and improved state-of-the art laser sources and diagnostic techniques so that optical or electrical measurements could be performed with unprecedented temporal resolution, typically in the picosecond or femtosecond domain.</p>					
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TABLE OF CONTENTS

Summary.....	3
I. Direct Time-Resolution of Velocity Overshoot in GaAs and Direct Observation of the Jones-Rees Effect	5
II. Direct Study of Resonant-Tunneling Transport	6
III. Experimental Investigation of Transport Between Quantum Wells	8
IV. Time-Resolved Observations of Electron-Phonon Relaxation During Femtosecond Laser Heating of Copper	8
V. Propagation of Picosecond Electrical Pulses on Superconducting (Ordinary or High-Temperature) Transmission Lines	9
VI. Component and Circuit Characterization (FET, HEMT, PBT, and MMIC).....	11
VII. Study of Broadband Analyzer Concepts	13
VIII. Contract Procurements	15
IX. Collaborations	15
X. Related Publications	20
XI. Presentations Subsequently Published	20
XII. Conference Presentations	21
XIII. Symposia and Colloquia	21
XIV. Patent Applications	22



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AFOSR URI
ANNUAL TECHNICAL REPORT
1987

The general objective of the AFOSR URI Center at Rochester is to investigate the physics of electronic microstructures using ultrafast optical techniques. To achieve this goal, we have developed and improved state-of-the-art laser sources and diagnostic techniques so that optical or electrical measurements could be performed with unprecedented temporal resolution, typically in the picosecond or femtosecond domain.

Some remarkable accomplishments have been obtained this past year:

1. Direct time resolution of velocity overshoot in GaAs and direct observation of the Jones-Rees effect.

Velocity overshoot in the subpicosecond time scale has been observed by studying the time evolution of the photocurrent produced by short optical pulses at different wavelengths. The velocity overshoot has been studied directly, as well as the Jones-Rees effect.

2. Direct study of resonant tunneling transport.

We have directly characterized the resonant-tunneling current, when the diode structure is driven quickly through its negative differential resistance region. The resonant-tunneling current reaches its steady-state value in a time of the order of 1 ps. This is in good agreement with the predictions made by H. C. Liu and D. D. Coon.

3. Optical techniques are being used to study the transport between semiconductor layers. These techniques use quantum wells as spatial probes. The tunneling time is being investigated using these techniques. The structures are grown by Cornell and by Thomson - CSF.

4. Time-resolved electron-phonon coupling constant interaction in metal films.

Electron-phonon interactions in copper have been time-resolved, and the hot electron population has been observed with temperatures of a thousand degrees above the lattice temperature. The electron-phonon coupling constant has been determined.

5. Picosecond electrical pulse propagation on ordinary and high temperature superconductors.

For high-speed electronic, microwave and communications applications, it is important to preserve a signal's integrity. This becomes increasingly difficult as the pulses become shorter and shorter. The only recourse is to use superconducting transmission lines. We have shown that picosecond pulses can propagate over

distances of more than 10 m (50 ns) with extremely small amounts of dispersion (1 ps/m). This dispersion, we believe, is mainly due to the dielectric.

The initial results were obtained with lead coaxial lines. A series of experiments have been performed with the newly discovered class of superconductor, (High- T_c), Y-Ba-Cu-O. Over distances of 5 mm, it was shown that the signal could propagate without absorption or attenuation at a fraction of the critical temperature. Close to the critical temperature, the signal experiences dispersion according to the BCS theory.

6. Switching time of high-speed three-terminal devices.

We are investigating the current switching times of devices such as the PBT (MIT Lincoln Laboratories), TEGFET (Thomson CSF), Pseudomorphic HEMT (GE) and lattice-mismatched HEMT (Cornell). This technique has been previously used to study the switching time of the TEGFET and PBT, where a gate voltage is instantaneously switched on. A study of the current switching time as a function of gate length should lead to information on the nonstationary transport in FET's

A new testing technique called the electro-optic finger probe technique has been demonstrated. This technique allows the temporal characterization of electrical signals in a noninvasive way with spatial and temporal resolutions, respectively, of 1 μm and less than 1 ps. MMIC circuits (32.5 GHz) from NASA Lewis Research Center have been tested using this technique.

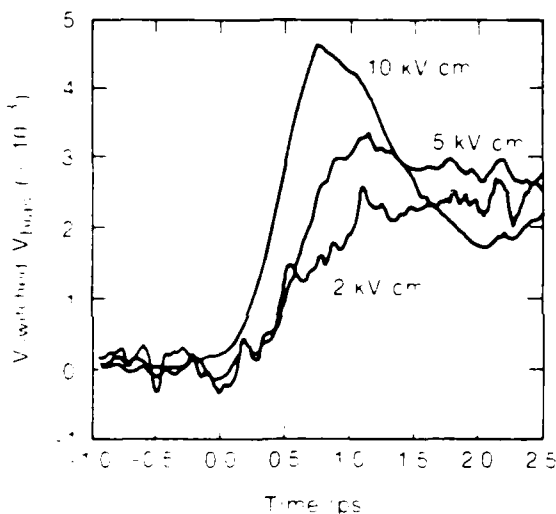
7. Study of broadband network analyzer concepts.

Complete understanding of devices and circuits requires the characterization of input, reflected and transmitted pulses. Concepts based on electro-optic sampling techniques are being tested to perform this task in the 0.1 - 1 THz range.

I. DIRECT TIME-RESOLUTION OF VELOCITY OVERSHOOT IN GaAs AND DIRECT OBSERVATION OF THE JONES-REES EFFECT

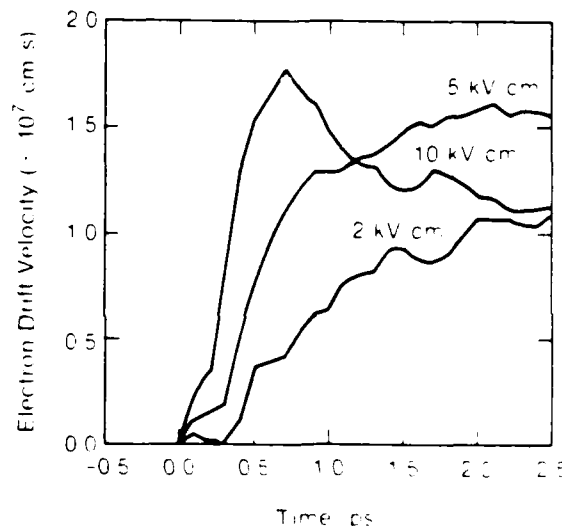
Graduate Students - K. Meyer, T. Norris, M. Pessot,
Professors - R. Grondin, G. Mourou

Time-resolved measurements of velocity overshoot in GaAs have been carried out using transient photoconductivity techniques. Initial experiments were conducted using 620-nm photoexcitation generated by a CPM laser; in this case, very significant photocurrent overshoot was observed on a 0.7 ps time scale, an effect which disappeared at low field (Fig. 1). These results are in good agreement with Monte Carlo calculations (Fig. 2). The experiments were repeated using 760 nm excitation; photocurrent overshoot was observed but not well resolved due to a limiting 300 fs laser pulse width. Agreement with calculations is achieved if a 0.9 ps sampling function is assumed (Fig. 3).



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Fig. 1 Monte Carlo simulation of the photocurrent produced at excitation wavelength $\lambda = 620$ nm.



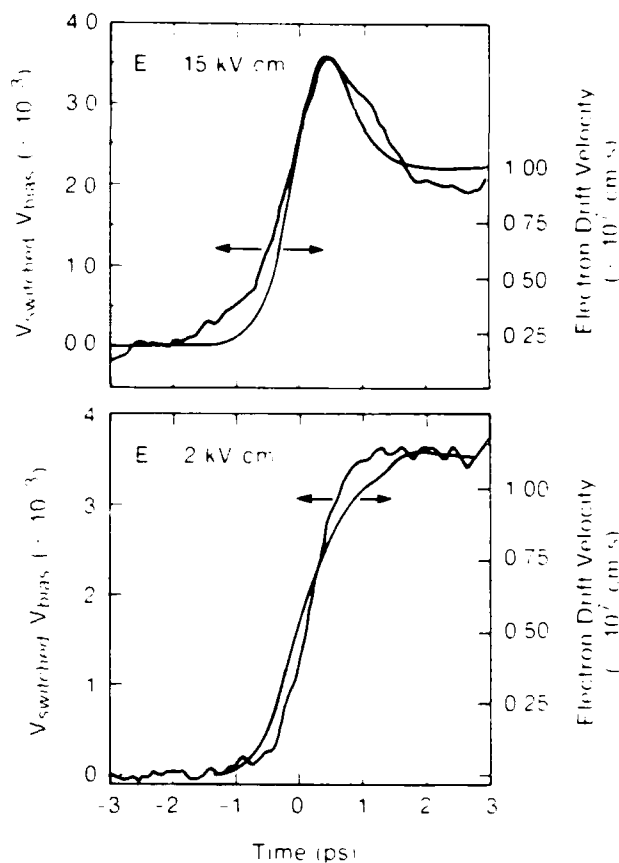
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Fig. 2 Photocurrent overshoot observed at 620 nm excitation for different electric fields.

In addition, we have observed for the first time the Jones-Rees effect, which manifests itself as a delay in the photogenerated current. The comparison between experimental values and theoretical predictions deduced from Monte Carlo simulation is shown in the following table.

	2 kV/cm	5 kV/cm	10 kV/cm
Monte Carlo Prediction	0.4 ± 0.05 ps	0.3 ps	0.1 ps
Experiment	0.33 ± 0.05 ps	0.35 ps	0.12 ps

Fig. 3 Photocurrent overshoot at 760 nm for electric fields of 2 kV/cm and 15 kV/cm. The overshoot is less pronounced than expected due to the pulse duration at this wavelength of 300 fs. The experimental curve and the convolution function assuming a response time of 0.9 ps are represented.



A new experiment for the measurement of the dynamic central-valley distribution function following photoexcitation has been demonstrated. The evolution of the distribution function has been measured during the first 2 ps with a variable applied field. Femtosecond thermalization of the carriers and field-induced carrier heating on a 400 fs time scale has been observed. Figure 4 shows the distribution function at low and high fields, captured .5 ps after excitation. A significant delay is observed in the hot electron distribution.

II. DIRECT STUDY OF RESONANT-TUNNELING TRANSPORT

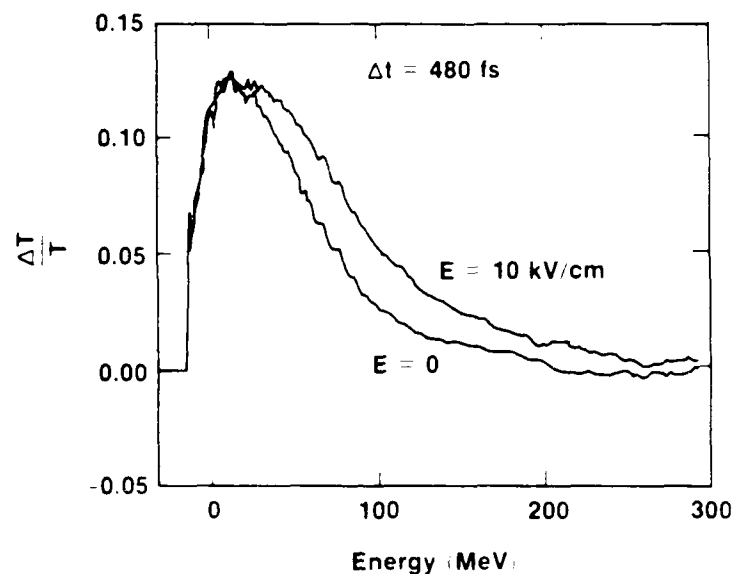
Graduate Student - J. Whitaker

Research Engineer - J. Nees

Professors - G. Mourou, T. Hsiang

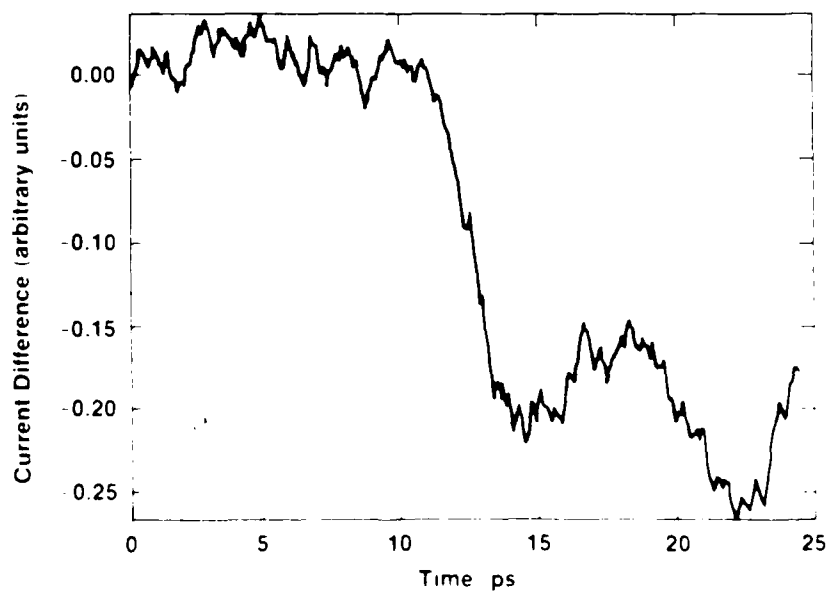
The switching time of a heterojunction double-barrier resonant-tunneling diode (RTD) has been measured using electro-optic sampling techniques. Quantum-mechanical tunneling in these single quantum wells is the fastest known charge-transport mechanism in semiconductors. This class of device exhibits such features as negative differential resistance (NDR), an extremely fast current response, and a high-frequency output when used as an oscillator. Now, using a laser-based sampling system having a demonstrated subpicosecond temporal response a switching time of less than 2 ps (see Fig. 5) has been

measured for a double-barrier RTD. This result indicates that either sequential or resonant tunneling occurs in the single picosecond time scale. A better temporal resolution (200 - 300 fs) and/or investigations at lower temperatures will be necessary to discriminate with certainty between sequential and resonant tunneling.



Z447

Fig. 4 Evolution of the distribution function as a function of field strength. The distribution function are captured 480 fs after photoexcitation



Z375

Fig. 5 Current switching time of a double-barrier resonant-tunneling diode. The switching time is less than 2 ps.

III. EXPERIMENTAL INVESTIGATION OF TRANSPORT BETWEEN QUANTUM WELLS

Graduate Students - T. Norris, M. Pessot, G. Sucha
Professors - R. S. Knox, G. Mourou

In order to directly time-resolve the basic physical processes involved in perpendicular transport and tunneling in semiconductor heterostructures, we have been applying the techniques of femtosecond spectroscopy. A femtosecond optical pulse is amplified and used to generate a white light continuum, which may be used for band-edge excitation and probing GaAs/AlGaAs heterostructures. We have performed preliminary modulated reflectivity experiments directed towards time resolving the tunneling of electrons between two weakly coupled quantum wells. In progress are experiments to probe the modulated absorption of the MQW structure in order to directly obtain the electron occupations in each well. Also in progress are experiments to time resolve the tunneling lifetime of electrons confined in a double barrier structure and to measure scattering rates between subbands in a short-period GaAs/AlAs superlattice.

IV. TIME-RESOLVED OBSERVATIONS OF ELECTRON-PHONON RELAXATION DURING FEMTOSECOND LASER HEATING OF COPPER

Graduate Students - M. Pessot, T. Norris, H. Chen, S. Horbatuck
Scientist - Hani Elsayed-Ali
Professor - G. Mourou

Thermal modulation of the optical properties of metals is a widely used technique in studying critical points in band structure. Recently the modulation of reflectivity of copper has been used to observe nonequilibrium electron-lattice temperatures during picosecond (~ 5 ps FWHM) laser heating of up to a few degrees. Although nonequilibrium heating was demonstrated in these experiments, the time resolution was insufficient to resolve electron-phonon relaxation. In a subsequent report, the phenomenon of thermally enhanced multiphoton photoemission was used to time-resolve electron-phonon relaxation in tungsten. Results indicated that such relaxation is accomplished in a few hundred femtoseconds. We now have obtained results using amplified 150–300 fs laser pulses to time-resolve electron-phonon relaxation by monitoring the laser-heating-induced modulation of the transmissivity of 200 Å copper films.

A 1 KHz synchronously amplified colliding-pulse, mode-locked laser ($\lambda = 620$ nm) was used for the pump-probe experiments. The sample was heated using the 620 nm fundamental. Probing was accomplished at 620 nm or using a 10 nm (FWHM) band from white light generated by focusing the probe beam on an ethylene glycol cell. The pump and probe were incident collinearly normal to the copper film (polarized perpendicular to each other) and focused to ~ 27 and ~ 14 μm diameter spots, respectively, such that the probe was in the center of the pump.

The transmissivity of the thin copper films at $\lambda = 620$ nm during laser heating (~ 300 fs FWHM) for different pump laser fluences have been studied. The initial response was found to be 1–4 ps increasing with the heating pulse fluence. This effect is due to larger differences between electron and lattice temperatures for higher fluences, so that more electron-phonon collisions are required for thermalization. A slower decay

(hundreds of picoseconds) of the lattice temperature (mainly due to diffusion) was observed.

Using white light in 10 nm steps from $\lambda = 560$ to 640 nm ($\lambda = 590$ nm corresponds to an electron transition from the top of the d-band to the Fermi level) showed similar behavior as when probing at $\lambda = 620$ nm.

In conclusion, we have directly measured the electron-phonon relaxation time in copper as a function of pump laser fluence and probe photon energy for $\lambda = 560$ to 640 nm. We have demonstrated nonequilibrium heating with a large ($\sim 1000^\circ\text{K}$) difference between electron and lattice temperatures. Electronic and lattice effects on the optical properties of copper were separated in time. Extension of probe measurements to the near IR and UV parts of the spectrum would separate effects of bound and free electrons on the optical properties and provide considerable information on the band structure.

V. PROPAGATION OF PICOSECOND ELECTRICAL PULSES ON SUPERCONDUCTING (ORDINARY OR HIGH-TEMPERATURE) TRANSMISSION LINES

Graduate Students - J. Chwalek, J. Whitaker

Scientist - D. Dykaar

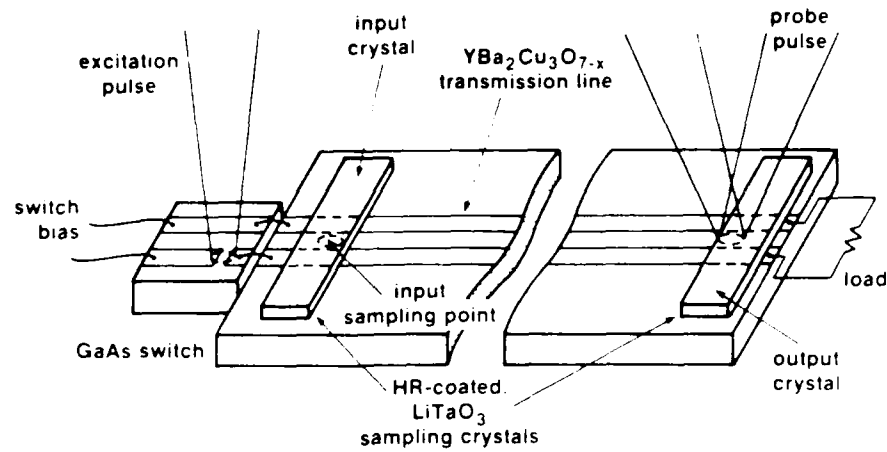
Professor - G. Mourou, T. Hsiang

The results of two propagation experiments is summarized. In one, a picosecond electrical pulse was propagated over a distance of 10 m on coaxial transmission lines, with virtually no dispersion. The other represents the first high-speed measurements made on a transmission line of the new ceramic superconductor, Y-Ba-Cu-O.

The experimental waveshapes were also simulated using an algorithm which takes into account the effects of the transmission line geometry, substrate material, and electrode conductivity. With this model, the evolution of ultrafast waveshapes are simulated, and the various characteristics of the distorted waveshapes attributed to modal dispersion, lossy substrates, and conductor losses. For the latter, skin effect losses are prominent at high frequencies for normal-metal electrodes, while both attenuation and a frequency-dependent phase velocity become important considerations near the energy gap frequencies associated with superconducting electrodes.

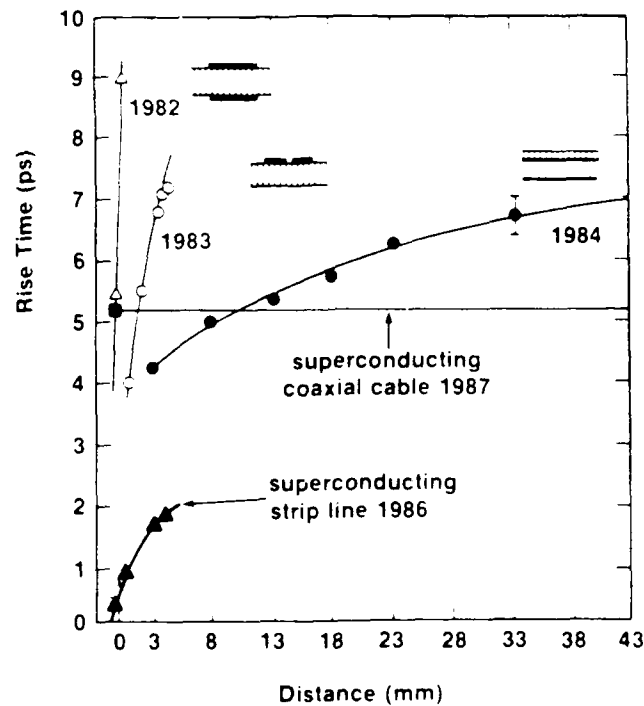
Figure 6 shows the testing geometry used to study the propagation of picosecond electrical pulses on coplanar transmission lines. The measurement is based on electro-optic sampling. The sampling was done in reflection mode which employed two high reflection dielectric coated LiTaO₃ crystals (located at either end of the transmission line) which served as the sampling points for the input and output pulses. The transmission lines were 5.4 mm long, 30 μm wide and separated by 30 μm . The thickness of the Y-Ba-Cu-O was 0.36 μm , and it was thermally deposited on yttrium stabilized ZrO₂.

Figure 7 shows the pulse rise time versus the propagation distance for various transmission lines with normal and superconducting electrodes. Note the increased performance due to superconducting electrodes over normal electrodes.



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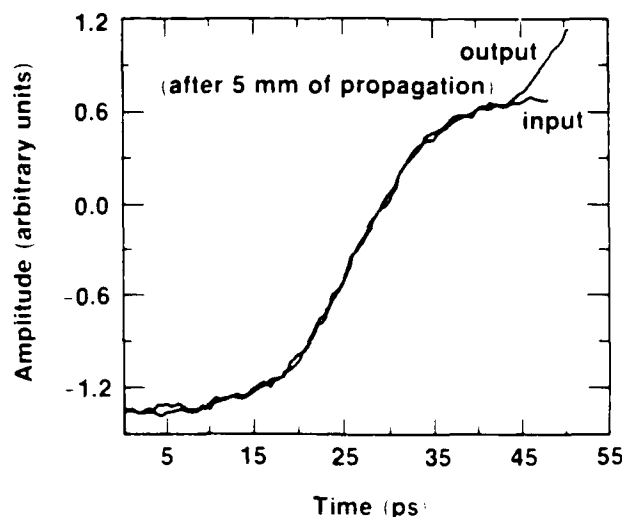
Fig. 6 Testing geometry to study the pulse propagation on a coplanar transmission line. The line is made of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ on cubic zirconia.



Z403

Fig. 7 Rise time versus propagation distance for various transmission lines. Note the dispersionless characteristics of the superconducting coaxial lines (10 fs/cm).

Figure 8 is a comparison between the input and output of the signal's leading edge. When the temperature of the sample is less than 20°K, the leading edge of both the input and output pulse are identical in amplitude and in shape. This suggests that at a good fraction of the critical temperature, pulses with frequency greater than 10 GHz can propagate with current densities as high as 1 MA/cm².



Z448

Fig. 8 Comparison between input and output of the signal leading edge produced by a photoconductive switch. The discrepancy between input and output comes from a reflection at the end of the line.

VI. COMPONENT AND CIRCUIT CHARACTERIZATION (FET, HEMT, PBT, AND MMIC)

Graduate Student - J. Whitaker

Research Engineer - J. Nees

Scientists - T. Jackson, D. Dykaar

Professor - G. Mourou, T. Hsiang

We have developed and studied a new optical technique which allows a substrate-independent study of electrical waveforms. This technique is called the electro-optic finger probe technique and consists of a small crystal of electro-optic material located in the fringing field of the device or circuit under study (see Fig. 9). A high reflectivity coating or total internal reflection is used to reflect back the probing beam. This powerful technique of noncontact probing now allows for versatile device probing on the picosecond and subpicosecond time scale. The majority of experiments performed at the center use this scheme.

One case where the finger probe is used and compared with the more conventional transmission scheme is the testing of a Texas Instruments MMIC. This single-stage, 32.5 GHz amplifier was provided by Kul Bhasin of NASA Lewis Research Center in Cleveland. Using coplanar striplines deposited on LiTaO₃, the device was found to have significant gain enhancement between 30 and 32.5 GHz (see Fig. 10). Also, an optimization of bias voltage was done showing the best gain around $V_d = 1.3$ V. Further study of the two- and three-stage amplifiers is now in progress.

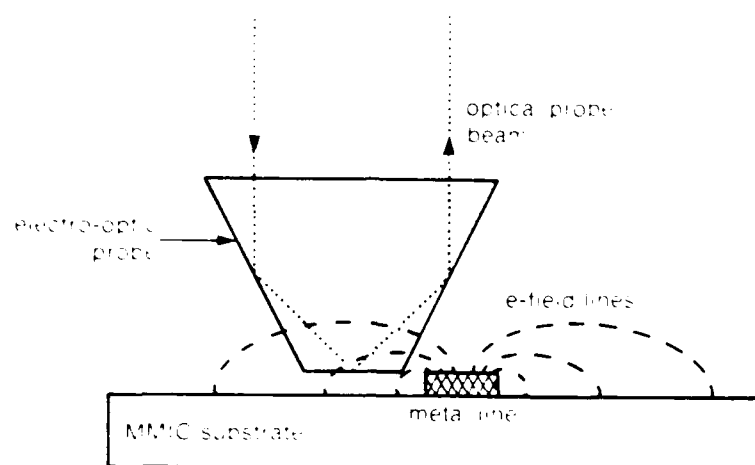
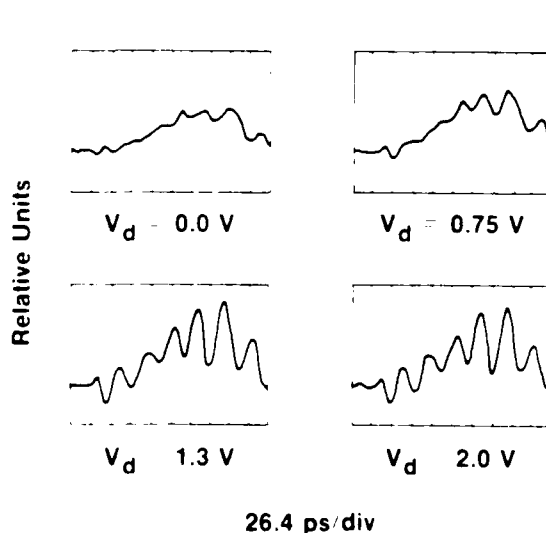
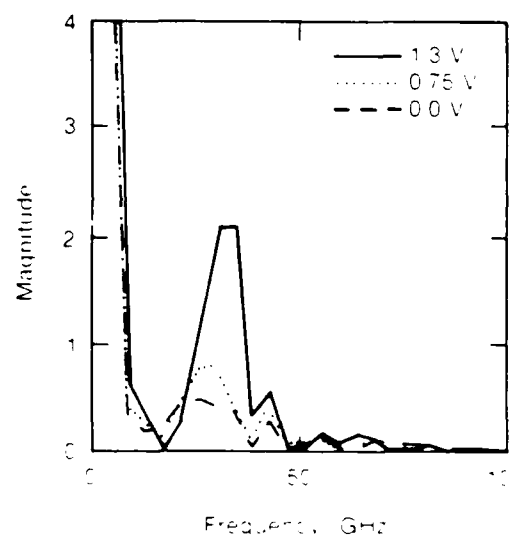


Fig. 9 Finger probe technique using total internal reflection. The small crystal is located in the fringing field of the circuit under test.



Z326

Fig. 10(a) Response of a MMIC, single stage amplifier to a short input pulse. The characterization has been performed with the finger probe.



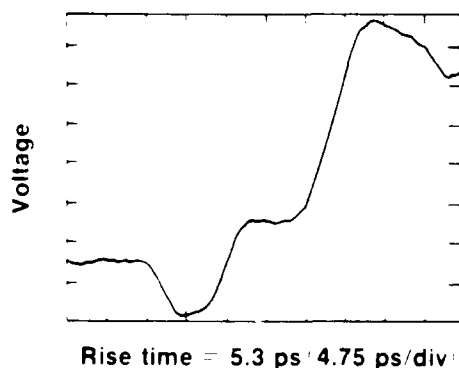
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Fig. 10(b) Fourier-Transformed of the temporal response showing the central frequency and narrow bandwidth of the amplifier.

Efforts have been made at Lincoln Laboratories to model the PBT results which were previously obtained at Rochester. A comparison between the experimental output waveform and the one resulting from the modeling is shown in Figs. 11 and 12.

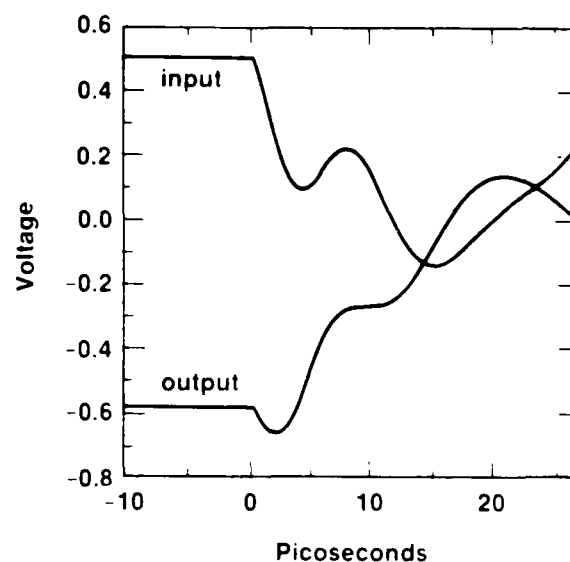
A new device carrier is being tested that will allow us to obtain useful information about the input signal which is critical for the eventual S-parameter study.

Preliminary characterization of a General Electric HEMT transistors has been performed.



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Fig. 11 Experimental switching output waveform from a PBT



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Fig. 12 Simulated input and output waveforms for the PBT

VII. STUDY OF BROADBAND ANALYZER CONCEPTS

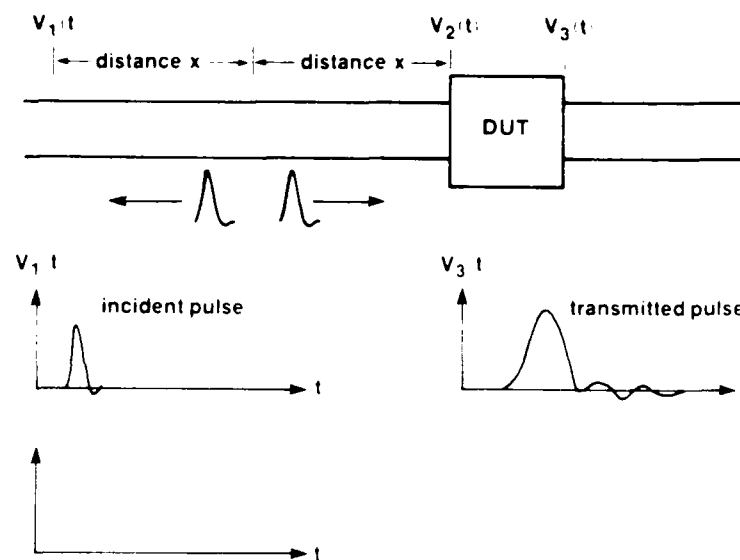
Graduate Student - J. Whitaker
 Research Engineer - J. Nees
 Scientists - D. Dykaar, T. Jackson
 Professor - G. Mourou

At present, the upper limit of electronic frequency-domain network analyzers using frequency mixing techniques and waveguides is 100 GHz. An alternative approach is to compute the scattering parameters of an electronic circuit from time domain data. One must, however, ensure that the test waveforms have sufficient high frequency energy and that errors do not result from aliasing and spectral leakage. Aliasing can be minimized by oversampling while spectral leakage can be avoided through appropriately windowing short test pulses produced using laser-driven ion-damaged photoconductive switches.

The remaining facet of a complete network analyzer under development at the Center is the transmission line environment in which a device resides during characterization. The identical pulse generation concept allows a test device's incident and reflected pulses to be distinguished without any de-embedding requirements.

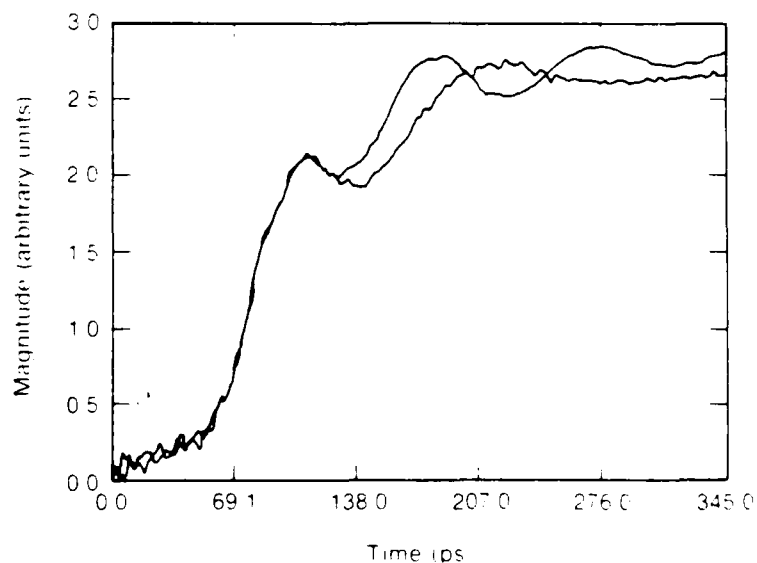
One of the concepts to characterize incident, reflected, and transmitted waveforms is shown in Fig. 13, where a pulse is produced by a photoconductive detector on a transmission line. The switch generates two identical pulses propagating in opposite directions (Fig. 13). The pulses measured at the device under test level $V_2(t)$ represent the algebraic sum of the incident plus reflected waveforms. $V_3(t)$ is the transmitted waveform. The incident waveform is measured at a distance equal to the switch DUT

distance as shown in Fig. 13. A study of the pulse quality has been performed and is shown in Fig. 14. The discrepancy observed in Fig. 14 between the two waveforms is due to a reflection at the end of the line. Presently the effort is concentrated on producing short pulses in the 5–10 ps range as opposed to step function-like pulses as shown in Fig. 14.



Z220

Fig. 13 Electro-optic network analyzer concept showing the possibility to measure input and reflected output waveforms



Z344

Fig. 14 Comparison between propagating and counter propagating waveforms

VIII. CONTRACT PROCUREMENTS

Of the total contract procurements for the first year, 42% or \$126,000 were let to small business concerns. Seven percent or \$21,000 was let to small and disadvantaged business concerns. Included in these amounts were 10 transactions totalling \$15,400 that were directed toward labor surplus areas.

IX. COLLABORATIONS

Collaborative research efforts have been intense during this first year. This is the list of the laboratories we have been interacting with.

LABORATORIES	INVESTIGATORS	PROJECTS
University of Illinois	Higman, Coleman	Hetrostructure Hot Electron Diodes
NASA Lewis Research Center	Kul Bhasin	Monolithic Microwave Integrated Circuits
General Electric	George Duh	High Electron Mobility Transistor
MIT Lincoln Lab	Sollner, Goodhue	Resonant Tunneling Diode
	Murphy	Permeable Base Transistor
Cornell University	Bhurman Eastman	High Tc Superconductor Travelling Wave Transistor
	Bill Schaff	MBE layers for keV
University of Rochester	Hsiang Kadin	Josephson Juntions, Devices High Tc Superconductor
Bell Northern	Paul Jay	FETs
Fujitsu	Osamu Wada	Photodiode
Arizona State University	Bob Grondin	Velocity Overshoot Monte Carlo Simulation
Scientific Research Association	M. Osman H. Grubin	Nonstationary Transport Monte Carlo Simulation

In addition two meetings were held successfully at Cornell and Rochester to promote the interaction between the two groups as well as two major conferences held at LLE at which government personnel were informed of the continuing progress in research being performed at the center. The agendas of the conferences are attached to illustrate the topics covered at the meetings.

Laboratory for Laser Energetics

250 East River Road

Rochester, New York 14623

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TEL 716 275 5101

Agenda 7 April 1987

*Discussions on Ultrafast Optics and Physics of Modern Devices
Tour of the Center for Ultrafast Sciences*

Held at the Laboratory for Laser Energetics
University of Rochester
250 East River Road
Rochester, NY 14623

8:30 - 8:40	Introduction	R. McCrory
8:40 - 8:50	Relationship of the U.S. Government and the Center for Ultrafast Sciences	G. Witt
8:50 - 9:20	The Air Force Ultrafast Science Center	G. Mourou
9:20 - 10:05	Rochester/Cornell Interaction	L. Eastman
10:05 - 10:20	Device and Circuit Characterization	D. Dykaar
10:20 - 10:35	<i>Break</i>	
10:35 - 10:50	Resonant Tunneling	J. Whitaker
10:50 - 11:05	Tunneling Experiment	T. Norris
11:05 - 11:20	Velocity Overshoot Experiment	K. Meyer
11:20 - 11:35	Velocity Overshoot Simulation	R. Grondin
11:35 - 11:50	Electro-Optic Network Analyzer	T. Jackson
11:50 - 11:30	Signal Extraction	J. Nees
11:30 - 12:05	Laser Sources for High-Speed Electronics	P. Bado
12:05 - 12:30	<i>Lunch</i>	

(continued on reverse side)

12:30 - 12:40	Role of the Center for Ultrafast Sciences with the College of Engineering and Applied Science at the University of Rochester	Dean B. Arden
12:40 - 13:10	Solid-State Reaction in the Picosecond Time Scale	H. Elsayed-Ali
13:10 - 14:40	Tour of the Ultrafast Science Center	
14:40 - 14:50	Role of the Center for Ultrafast Sciences with the University of Rochester	Pres. O'Brien
14:50 - 15:10	Role of Superconductors in High-Speed Electronics	R. Sobolewski
15:10 - 15:30	<i>Discussion and Wrap-up Session</i>	

TECHNICAL PROGRAM

URI REVIEW

November 5 - 6, 1987
(Coliseum)

Thursday, November 5th, Afternoon

2:30 PM	Welcome	Dean B. Arden Univ. of Rochester
2:40	Rochester Program an Overview	G. Mourou Univ. of Rochester
3:00	General Overview and Summary of Interaction	L.F. Eastman Cornell University
3:20	Theory of Transport Between Quantum Wells	R.S. Knox Univ. of Rochester
3:50	BREAK	
4:10	Switching Mechanisms in Heterostructure Hot Electron Diode	J.J. Coleman Univ. of Illinois
4:20	Transport Between Quantum Wells (Experiments)	T. Norris Univ. of Rochester
4:35	Tunneling Time Measurement by Photoluminescence	J. Song Cornell University
4:45	The Resonant Tunneling Diode	R.A. Murphy MIT Lincoln Lab
4:55	Switching Time of Resonant Tunneling Diode (Theory)	D. Coon Univ. of Pittsburgh
5:05	Switching Time of Resonant Tunneling Diode (Experiment)	J. Whitaker Univ. of Rochester
5:15	Investigation by Raman Spectroscopy of the Effect of Growth Stops at GaAs/GaAlAs Interfaces	J.T. Bradshaw Cornell University

TECHNICAL PROGRAM URI REVIEW

November 5 - 6, 1987
(Coliseum)

Continued

Friday, November 6, Morning

8:30 AM	Velocity Overshoot Monte Carlo Simulation	R. Grondin Arizona State Univ.
8:45	Velocity Overshoot Experimental Study	K. Meyer Univ. of Rochester
9:00	Electron Phonon Interaction A Picosecond Study	H. Elsayed-Ali Univ. of Rochester
9:20	Traveling Wave HEMT	D. Shire (Cornell Univ.) T. Jackson (Univ of Roch)
9:35	High Temperature Superconductors	R. Buhrman Cornell University
9:50	Propagation of Picosecond Electrical Pulses on Superconducting Lines	J. Chwalek Univ. of Rochester
10:05	BREAK	
10:20	Device and Test Interactions	P. Tasker Cornell University
10:35	High Speed Device Characterization	D. Dykaar Univ. of Rochester
10:50	MMIC Characterization	J. Nees, J. Whitaker Univ. of Rochester
11:05	Electro-optic Network Analyzer	T. Jackson Univ. of Rochester
11:20	MODFET Operation Beyond the Charge Control Model	L.D. Nguyen Cornell University
11:35	Closing Remarks	G. Mourou, Rochester L. Eastman, Cornell G. Witt, AFOSR

X. RELATED PUBLICATIONS

- M. Pessot and G. Mourou, "Increased Power Handling Capacity of Single-Mode Fibers Through External Pulse Manipulation," accepted for publication by Opt. Lett..
- T. Y. Hsiang, J. F. Whitaker, R. Sobolewski, D. R. Dykaar, and G. A. Mourou, "Propagation Characteristics of Picosecond Electrical Transients on Coplanar Striplines," Appl. Phys. Lett. **51**, 1551-1553 (November 1987).
- J. F. Whitaker, T. B. Norris, G. Mourou, T. Y. Hsiang, "Pulse Dispersion and Shaping in Microstrip Lines," IEEE Trans. Microwave Theory Tech. **MTT-35**, 41-47 (January 1987).
- D. R. Dykaar, R. Sobolewski, T. Y. Hsiang, and G. A. Mourou, "Response of a Josephson Junction to a Stepped Voltage Pulse," IEEE Trans. Magn. **MAG-23**, 767-770 (March 1987).
- M. Pessot, P. Maine, and G. Mourou, "1000 Times Expansion/Compression of Optical Pulses for Chirped Pulse Amplification," Opt. Commun. **62**, 419-421 (June 1987).
- T. Jackson, J. Nees, R. Vallee, and G. Mourou, "Novel Method for Ultrahigh-Frequency Electro-Optic Time-Domain Reflectometry," Electron. Lett. **23**, 1130-1131 (October 1987).
- J. Nees and G. Mourou, "Noncontact Electro-Optic Sampling with a GaAs Injection Laser," Electron. Lett. **22**, 918-919 (August 1986).
- J. F. Whitaker and G. A. Mourou, "Optical Reconfiguration of Electrical Networks," Electron. Lett. **22**, 899-900 (August 1986).

XI. PRESENTATIONS SUBSEQUENTLY PUBLISHED

- G. Mourou, K. Meyer, J. Whitaker, M. Pessot, and R. R. Grondin, "Ultrafast Optics Applied to Modern Device Research," presented at the IEEE/OSA Meeting on Picosecond Electronics and Optoelectronics, 14-16 January 1987, Lake Tahoe, NV and published in Picosecond Electronics and Optoelectronics II, ed. F. J. Leonberger, C. H. Lee, F. Capasso, and H. Morkoc (Springer-Verlag, Berlin, Heidelberg, New York, London, Paris, Tokyo, 1987).
- J. Nees and W. Williamson "A technique for Wing Suppressed IR Sampling," presented at the IEEE/OSA Meeting on Picosecond Electronics and Optoelectronics, 14-16 January 1987, Lake Tahoe, NV and published in Picosecond Electronics and Optoelectronics II, ed. F. J. Leonberger, C. H. Lee, F. Capasso, and H. Morkoc (Springer-Verlag, Berlin, Heidelberg, New York, London, Paris, Tokyo, 1987).
- G. Mourou, "Electron Device Probing in the Femtosecond Time Scale," presented at the IEEE/OSA Meeting on Picosecond Electronics and Optoelectronics, 14-16 January 1987, Lake Tahoe, NV and published in Picosecond Electronics and Optoelectronics II, ed. F. J. Leonberger, C. H. Lee, F. Capasso, and H. Morkoc (Springer-Verlag, Berlin, Heidelberg, New York, London, Paris, Tokyo, 1987).

XII. CONFERENCE PRESENTATIONS

- G. Mourou, "Generation of Ultrahigh Peak Power Pulses by the Technique of Chirped Pulse Amplification," Invited presentation at the OSA Annual Meeting, 20-23 October 1987, Rochester, NY.
- D.R. Dykaar, R. Sobolewski, J. M. Chwalek, T. Y. Hsiang, and G. A. Mourou, "Electro-Optic Sampler for Characterization of Devices in Cryogenic Environment," presented at the International Cryogenic Materials Conference, Cryogenic Engineering Conference, 14-18 June 1987, Batavia, IL.

- R. Sobolewski, D. R. Dykaar, and T. Y. Hsiang, "Chaos in Josephson Junctions Induced by Picosecond Current Pulses," presented at the XVIII International Conference on Low Temperature Physics, 20-26 August 1987, Kyoto Japan.
- G. A. Mourou, "Electro-Optic Sampling Technique and Its Application to Components and Circuit Characterization," presented at the ECS Symposium on Bean Testing, 10-15 May 1987, Philadelphia, PA.
- G. A. Mourou, "Femtosecond Optical Pulses and Applications," invited presented at the Conference on Electro-Optics/Laser '87, 16-18 April 1987 in Tokyo, Japan.
- G. A. Mourou, "Impact of Ultrafast Optics in High-Speed Electronics," invited presentation at the SPIE Conference on Novel Optoelectronic Devices, 30 March - 3 April 1987, The Netherlands.
- P. Maine, D. Strickland, M. Bouvier, and G. Mourou, "Amplification of Picosecond Pulses to the Terawatt Level by Chirped Pulse Amplification and Compression," present at CLEO '87, 27 April - 1 May 1987, Baltimore, MD.
- G. A. Mourou, "Ultrafast Optics Applied to Modern Electronic Device Research," invited presentation at IQEC '87, 27 April - 1 May 1987, Baltimore, MD.
- G. A. Mourou, "Direct Investigation of Nonequilibrium Transport Using Ultrafast Optical Techniques," invited presentation at the Ballistic Electrons Symposium, 22-27 March 1987, Santa Barbara, CA.
- D. R. Dykaar, R. Sobolewski, G. A. Mourou, and T. Y. Hsiang, "Time Domain Characterization of Josephson Tunnel Junctions," presented at the American Physical Society Conference, 16-20 March 1987, New York, NY.
- J. F. Whitaker, R. Sobolewski, D. R. Dykaar, G. A. Mourou, and T. Y. Hsiang, "Picosecond Pulse Propagation on Superconducting Microstrip and Coplanar Transmission Lines," presented at the American Physical Society Conference, 16-20 March 1987, New York, NY.
- G. Mourou, "Impact of Ultrafast Optics in High-Speed Electronics," presented at the Southeastern Section of the American Physical Society Conference, 20-22 November 1987, Williamsburg, VA.

XIII. SYMPOSIA AND COLLOQUIA

G. A. Mourou gave presentations on the general topic of the Impact of Ultrafast Optics in High-Speed Electronics at the following locations:

15 October 1987	University of Illinois
25 September 1987	AT&T Bell Labs
3 September 1987	U. S./Japan Roundtable at Stanford University
25 August 1987	University of Michigan
26 June 1987	Sandia National Labs
15 June 1987	SDIO Review Meeting in Washington, DC
27 May 1987	University of Michigan
4 May 1987	Army Research Office
30 March 1987	Thomson - CSF
27 February 1987	DARPA Review Meeting in San Francisco, CA
23 February 1987	Florida State University

XIV. PATENT APPLICATIONS

Inventor(s) — J. A. Nees, G. A. Mourou, and T. A. Jackson

UR-0088, Serial No. 21,089; filed 03/03/87

Status: Under Amendment

Title: Electro-Optic Measurement (Network Analysis) System

Abstract: An electro-optic sampling system for characterizing devices over a bandwidth extending to upper microwave frequencies (>100 GHz) waveforms are sampled at spaced locations from the device along strip lines on electro-optic material. These waveforms are processed to determine scattering parameters of the device.

Inventor(s) — M. Pessot and G. Mourou

UR-0093, Serial No. 104,749; filed 10/5/87

Status: Awaiting Action

Title: Method for Optical Pulse Transmission Through Optical Fibers Which Increases the Pulse Power Handling Capacity of the Fibers

Abstract: Nonlinear effects on fiber optic transmission are avoided by stretching the optical pulses (which may be modulated to carry data) before launching them into the fiber. This reduces peak power of the pulses while increasing average power.

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